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Tool path generation method for five-axis flank milling of corner by considering dynamic characteristics of machine tool

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Abstract

During the corner machining process of 5-axis flank milling, the sharp change of tool path and tool orientation may lead to a dramatic increase of the milling force and tool vibration, which gravely impacts the machining quality. In order to address this issue, a 5-axis flank milling tool path generation method for corners by considering the dynamic characteristics of machine tool is presented in this paper. To be specific, firstly, the allowance information model of corner is built according to the part model and roughing information. Secondly, the tool trajectory based on clothoid curve and milling force constraint is optimized. And then, the tool orientation based on tool trajectories is optimized. Finally, the 5-axis flank milling tool path is generated by considering the dynamic characteristics of machine tool and the milling force constraint. The remaining materials of corner can be removed uniformly using the proposed tool path, and the curvature of the tool path is continuous. Simulation results show that the machined surface of corner is smooth, and the proposed tool path is suitable for corner machining.

Keywords: Five-axis; Flank milling; Dynamic characteristics; Tool path; Corner

1. Introduction

The aircraft structural parts are important parts to form the body skeleton and aerodynamic shape of aircrafts, which are designed with many pockets to meet the light weight and strength requirement. The machining accuracy of pocket flank is quite high, sometimes 1.6μm or 0.8μm for key parts. There are a large number of corners connecting the adjacent flanks. As shown in the fig 1, the model of a typical aircraft structural part has almost two hundred corners. And some flanks are ruled surface. Because of its complex shape and high accuracy requirement, five-axis flank milling is often used for corner machining.

During the corner machining process of 5-axis flank milling, the mutational tool orientations and sharp points of tool path may result in dramatic change of machining width and cutting force, which can lead to severe vibration of cutting tool and machine tool, affect the machining quality of workpiece or even result in the scrapping of parts [1], especially for difficult-to-machine materials such as titanium alloy. In addition, the rapid change of the curvature of tool path curve requires higher performance in dynamic characteristics of machine tool. Once the dynamic characteristics of machine tool cannot meet requirements, the machining quality, precision and efficiency of workpiece will be affected [2]. Proper tool paths optimization attribute to machining quality. By considering the constraints of dynamic characteristics of machine tool and cutting force, the machining process can be more stable, and the machining quality and product correct rate will be improved.

In order to improve the machining quality of flank milling, the research communities have made many efforts, mainly divided into two aspects:

To reducing the cutting force, Choy et al. [3] presented a corner-looping based tool path for pocket milling. Rahman et al. [4] proposed a tool path generation method by a constraint of cutting width and feed speed. Gao et al. [5] proposed a corner machining strategy with constant contact cutting angle.

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Kim [6,7] presented an optimized tool path strategy respectively for the conventional tool path and direction parallel path, which maintained a constant material removal rate. The studies above proposed methods to reduce the milling force of corner. However, without considering the dynamic characteristics of machine tool, the curvatures of those tool paths are not continuous. Sui et al. [8] introduced a combination strategy of corner-looping milling and clothoid curve transition, which considering the milling force and dynamic characteristics of machine tool. But the method is not suitable for five-axis milling.

Optimizing the continuity of five-axis tool path, Shi et al. [9] proposed a smoothing method to round corners by using a pair of quintic PH curves. Chu et al. [10] proposed a method to generate a spline-curve constrained tool path that produces minimized geometrical deviations on the machined surface. Zhu et al. [11] proposed a global optimization method for five-axis flank milling tool path by using the distance function. Gong et al. [12] proposed a method reduce the machining error by constraints of tangential angle and minimum error. Dai et al. [13] calculated the intial tool paths by a kind of numerical methods. Castagnetti et al. [14] improved the kinematic behaviour of machine tools during milling using the Domain of Admissible Orientation (DAO) concept, Wang et al. [15] proposed an optimal method that guarantees an interference-free current tool path as well as the smallest change between adjacent tool orientations. The studies above proposed methods to smooth tool trajectories and tool orientations. However, the remaining materials distribute unevenly in the corner. While the five-axis tool path is G^2 continuous, the unstable milling force may lead to severe vibration of machine tool.

To address this problem, a tool path generation method for five-axis flank milling of corner is presented in this paper, which is synthetically according to the dynamic characteristics of machine tool as well as the constraint of the milling force. A simple but effective method is introduced to calculated tool orientations.

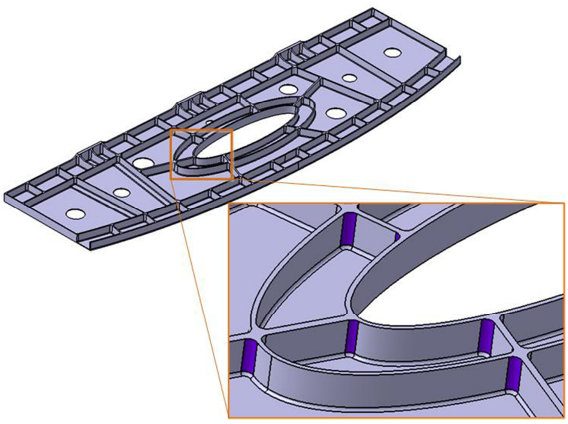

Fig. 1. An typical aircraft structural part with plenty of corners.

2. The overall of the proposed tool path generation method

In order to avoid the great change of cutting force during the corner flank machining process and to decrease the vibration of cutting tool and machine tool caused by the changing curvature of tool path, a tool path generation algorithm using the combination strategy of corner-looping milling and clothoid curve is proposed by the constraints of dynamic characteristics of machine tool and cutting force. The algorithm of the tool path generation process is shown in Fig. 2.

Firstly, the allowance information model of corner is built according to the part model and roughing information. Secondly, optimize the tool trajectory based on clothoid curve and milling force constraint. And then, the tool orientation based on tool trajectories is calculated. Finally, the 5-axis flank milling tool path is generated with the consideration of the dynamic characteristics of tool machine and milling force constraint.

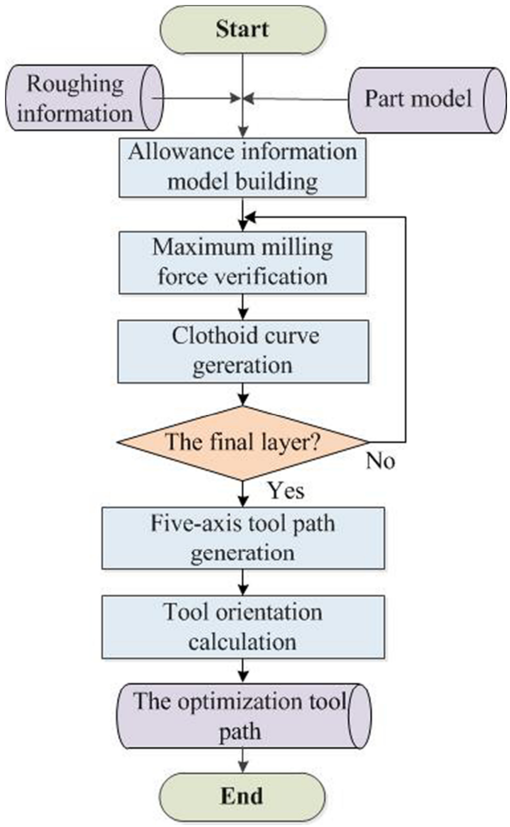

Fig. 2.The flow chart of tool path generation algorithm.

3. Tool path generation and optimization approach

The five-axis tool path is usually described by two trajectories. One trajectory describes the position of the tool tip point. And the other one describes the position of the second point on the tool axis. And they are generated based on constraints of dynamic characteristics of machine tool and cutting force. If we want to predict the milling force, the roughing allowance information model should be built at first.

3.1. The model of roughing allowance information

The roughing allowance information model is the basis for the generation of tool path, which is built based on the cutting tool information and roughing tool path. The roughing allowance for corner is shown in Fig. 3. The circle center of the corner allowance is used as the origin to construct local coordinate system. And then the allowance surface of roughing can be expressed by the following formulas:

$Q_0P_0Q_1P_1$:

$$y = R_d, \begin{cases} 0 \le x \le L_{Q_1P_1} \\ 0 \le z \le h \end{cases} \tag{1}$$

$R_0Q_0R_1Q_1$:

$$x^2+y^2=R_d^2, \begin{cases} 0<\theta<\pi/2, \begin{cases} -R_d \leqslant x \leqslant 0 \\ -R_d\cos\theta \leqslant y \leqslant R_d \\ 0 \le z \le h \end{cases} \\ \pi/2 \le \theta \le \pi, \begin{cases} -R_d\sin\theta \leqslant x \leqslant 0 \\ -R_d\cos\theta \leqslant y \leqslant R_d \\ 0 \le z \le h \end{cases} \end{cases} \tag{2}$$

$R_0S_0R_1S_1$:

$$y = -x\tan\theta - \frac{R_d}{\cos\theta},$$
$$0<\theta<\pi/2, \begin{cases} -R_d\sin\theta \leqslant x \leqslant -R_d\sin\theta + L_{R_1S_1}\cos\theta \\ -R_d\cos\theta - L_{R_1S_1}\sin\theta \leqslant y \leqslant -R_d\cos\theta \\ 0 \le z \le h \end{cases} \tag{3}$$
$$\pi/2 \le \theta \le \pi, \begin{cases} -R_d\sin\theta + L_{R_1S_1}\cos\theta \leqslant x \leqslant -R_d\sin\theta \\ -R_d\cos\theta - L_{R_1S_1}\sin\theta \leqslant y \leqslant -R_d\cos\theta \\ 0 \le z \le h \end{cases}$$

Where the parameter θ is the angle of the corner, and the notation R_d represents the radius of the allowance circle R_1Q_1, which is equal to the sum of corner tool path radius R_p and the cutter radius R_t for roughing. The notations $L_{R_1S_1}$ and $L_{Q_1P_1}$ are the length of allowance curve sidewalls respectively.

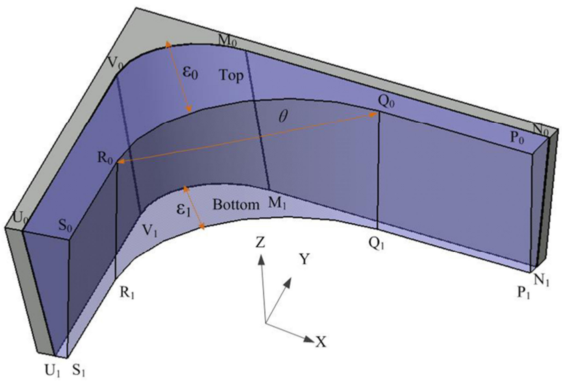

Fig. 3. The roughing remains in the corner.

3.2. G^2 continuous tool trajectory based on clothoid curve

In order to decrease the vibration of machine tool and improve the machining quality, the dynamic characteristics of machine tool are analyzed. By equation 4 and 5, the value of the acceleration is a positive correlation to tool path curvature. The value of jerk determines the changing speed of the tool path curvature. Considering the dynamic characteristics of the NC machine, and to keep the jerk at a minimum value as much as possible, the curvature should change equably the same way. In addition, the changing rate should be kept at a minimum value as long as the processing requirement is being satisfied.

$$\vec{a} = \mathrm{d}V/\mathrm{d}t \cdot \vec{\tau} + V^2 \rho \cdot \vec{n} \tag{4}$$

$$\vec{j} = V^2\, d\rho/dt\, \vec{n} - V^3 \rho^2\, \vec{n} \tag{5}$$

According to the definition, the curvature of clothoid curve changes uniformly with its length. And the corner-looping strategy can reduce the milling force in the corner. So a combination strategy of corner-looping milling and clothoid curve transition will be adopted in the corner to guarantee the continuity of tool path curvature and the stability of milling force, and decrease the vibration of machine tool during the process of machining. Two trajectories describing the five-axis tool path can be generated through similar method. The generation method is shown as follow:

As shown in the fig 4, the first layer of tool trajectory consists of line, arc and clothoid curve. AB and CD are two clothoid curves. BC is a segment of circular arc. A, D are the start points of clothoid curve, and build local coordinates shown in the fig 4. The clothoid curves can be expressed using the following formula:

$$\begin{cases} x = l - \frac{P^2}{6}l^3 - \frac{PQ}{4}l^4 - \left(\frac{Q^2}{10} - \frac{P^4}{120}\right)l^5 + \frac{P^3Q}{36}l^6 + \frac{P^2Q^2}{28}l^{7^9} \\ y = \frac{P}{2}l^2 + \frac{Q}{3}l^3 - \frac{P^3}{24}l^4 - \frac{P^2Q}{10}l^5 - \left(\frac{PQ^2}{12} - \frac{P^5}{720}\right)l^6 - \left(\frac{Q^3}{42} - \frac{P^4Q}{168}\right)l^7 \end{cases} \tag{6}$$

Where the parameter l represents the arc length from current point to start point, and the symbols P and Q can be expressed as follows:

$$\begin{cases} P = \rho_1 \\ Q = (\rho_2 - \rho_1)/2L = 1/2C \end{cases} \tag{7}$$

Where the parameters ρ_1 and ρ_2 are the curvatures of clothoid curve at the start and current point. The shape of clothoid curve will change with the parameters C.

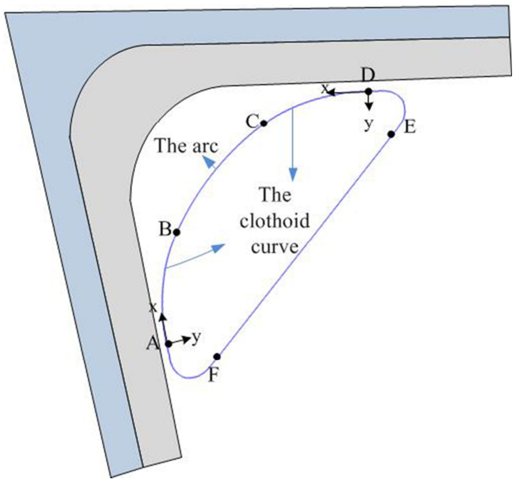

Fig. 4. The first layer of tool trajectory of corner.

To guarantee the G^2 continuity of tool trajectory, the curves should share a common tangent direction and a common center of curvature at the join points B, C. So the join points B, C of arc and clothoid curve can be generated through formula:

$$\begin{cases} R = 2Ql + P \\ X = l - \dfrac{P^2}{6} l^3 - \dfrac{PQ}{4} l^4 - \ldots \\ Y = \dfrac{P}{2} l^2 + \dfrac{Q}{3} l^3 - \dfrac{P^3}{24} l^4 - \ldots \\ Y_1 = kX_1 + t \\ \beta = Pl + Ql^2 \\ \tan\beta = \dfrac{X - X_1}{Y_1 - Y} \\ R = \sqrt{(X - X_1)^2 + (Y - Y_1)^2} \end{cases} \tag{8}$$

Where the parameters R and l are the radius of the arc and the length of clothoid curve respectively. The symbols X, Y, X_1 and Y_1 are the coordinate of connection point and the center point of the solving arc. The character β is the intersection angle between tangent vectors of clothoid curve at the start and end point. Finally, the parameters k and t are constants for angular bisector of corner.

The maximum cutting force needs to be verified for the series of clothoid curves and arcs. The verification method has been described in the thesis [8]. After the ABCD, DEFA is generated to form a looping curve. Not moving materials, DEFA usually has a high feed speed. To avoid the vibration of machine tool, DE and FA are a pair of clothoid curves respectively. And EF is a single line connecting clothoid curves. Finally, the radial layering of tool path for corner areas can be generated by the same way, shown as Fig .5.

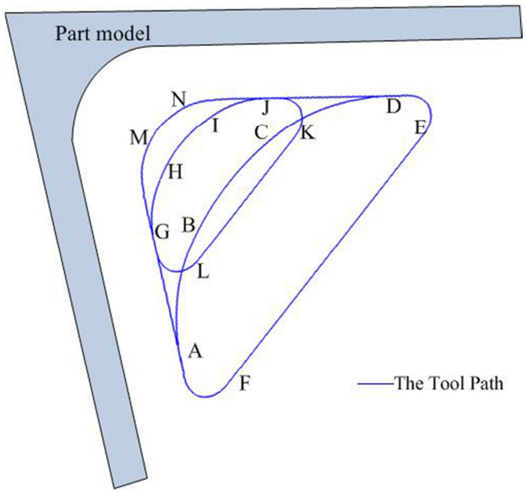

Fig. 5. The whole tool trajectory of the corner.

The generation method of the other tool trajectory has a small difference. Instead of the milling force, the other tool trajectory is layered based on the layering number of the before one. From the roughing allowance information model, we can know that ε_0 is bigger than ε_1. So the top trajectory should be generated at first to guarantee the milling force smaller than the limit all the way. The five-axis tool path of corner has top and bottom trajectories shown in the fig 6, which are mixtures of line, arc and clothoid curve.

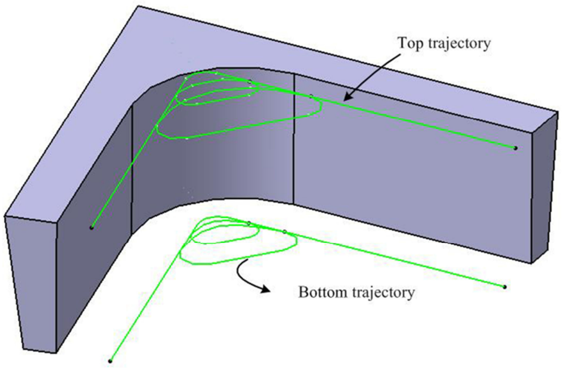

Fig. 6. The G^2 continuous two trajectories of corner.

3.3. Tool orientation calculation and optimization

Dramatic change of tool orientation during machining process also could lead to severe vibration of cutting tool and machining tool and affect the machining quality seriously. To solve this problem, a constraint of tool orientation is adopted.

As shown in the fig 7, the change of adjacent tool orientation is approximately represented as:

$$\nabla V(t) = Q_{t-1}Q_t - P_{t-1}P_t \tag{9}$$

$$a = Q_{t-1}Q_t / P_{t-1}P_t \tag{10}$$

If the a is a constant, the tool orientation change uniformly. Parameterize the bottom trajectory for the tool tip movement according to its arc length, and it can get discrete cutting location points corresponding to parameter t_{bottom}. To get the orientation of tool, the second point on the tool axis must be got, too. The top trajectory for the tool tip movement is parameterized according to formula 10, and the parameter $t_{top}= t_{bottom}=t$, shown as fig 7. The normal tool orientation vector at reference point $[P(t),Q(t)]^T$ is represented as formula :

$$V(t) = \frac{L_{top}(t) - L_{bottom}(t)}{\left\| L_{top}(t) - L_{bottom}(t) \right\|} = \frac{Q(t) - P(t)}{\left\| Q(t) - P(t) \right\|}$$

(11)

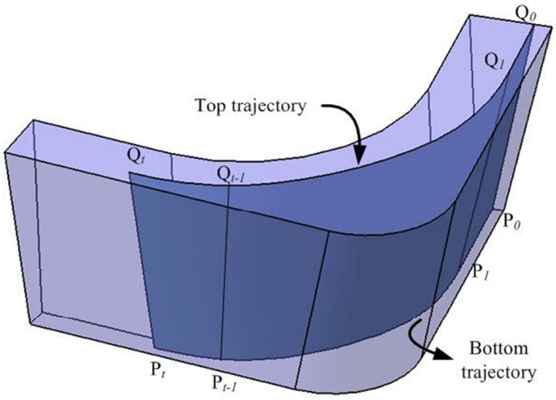

Fig. 7. The calculation of tool orientations.

4. Simulation results

As shown in Fig. 8, a corner model of pocket on aircraft structural part with ruled surfaces is used as an example for simulated experiment to verify the applicability of the proposed tool path. The flanks of corner model are titled. In the Fig. 9, the tool path of corner is generated based on the method in this paper. The analysis result of the first layer tool path is shown in the Fig. 10. The changing process of curvature is continuous. Simulation result is shown in the Fig 11, and the finished surface is smooth.

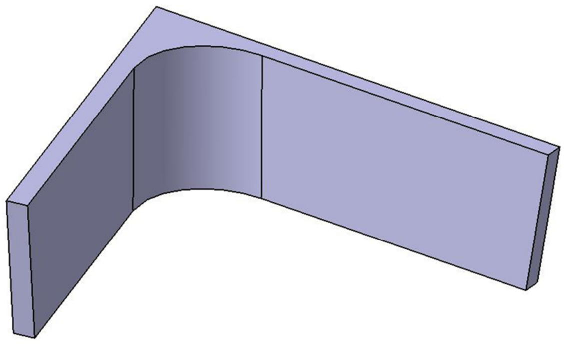

Fig. 8. The corner model with ruled surfaces.

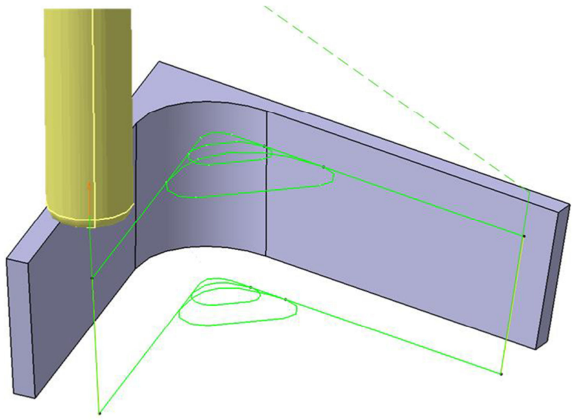

Fig. 9. The tool path of corner using the method in this paper.

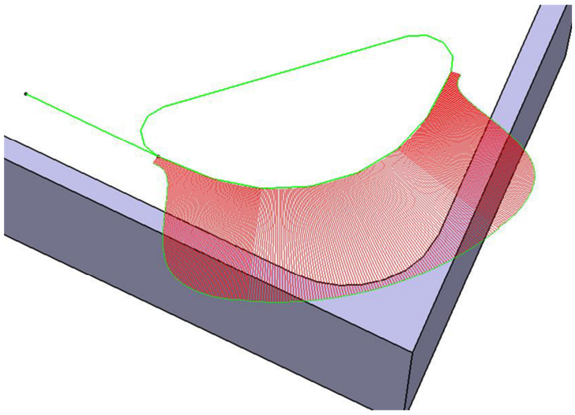

Fig. 10. The analysis result of the first layer of the tool path.

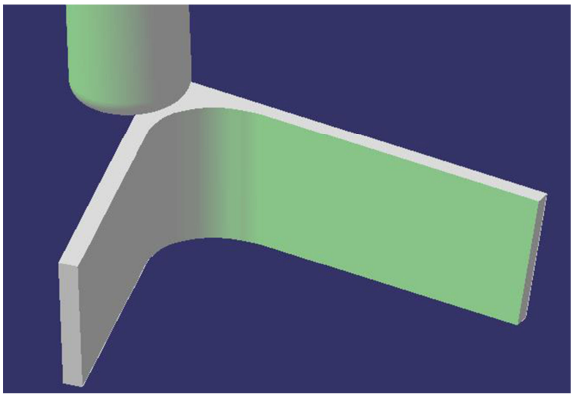

Fig. 11. The simulation result of the proposed tool path.

5. Conclusions and future work

To keep the five-axis flank milling process of corner stable, and avoid the sharp change of tool path and tool orientation, a combination strategy of corner-looping milling and clothoid curve is proposed. The remaining materials distribute unevenly in the corner. And the cutting force is constrained by limiting the cutting width during the machining process, and the change of tool path curve curvature is satisfied with the dynamic characteristics of machine tool by using clothoid curve.

Although some promising results have been obtained, there is still much work required to be researched furthermore. In this paper, the tool orientation is optimized by minimizing the change of adjacent tool orientation. The explicit correlations of tool orientation to the dynamic characteristics of tool machine will be studied in our future work. Besides, the tool path generation algorithm under the condition of variable feed rate will be studied.

Acknowledgements

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